Electromagnetic Analysis of Transient Forces Due to Disrupted Plasma Currents on the ITER Shield Modules

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Abstract— **This paper describes the electromagnetic analysis that has been completed using the OPERA-3d product to characterize the forces on the ITER shield modules as part of the conceptual design. These forces exist due to the interaction of the eddy currents induced in the shield modules and the large magnetic fields present in the tokamak.**

Keywords-component; Eddy currents; Electromagnetic force computation; ITER

I. Introduction

ITER is a joint international research and development project formed to demonstrate the scientific and technical feasibility of fusion power. The geometry of ITER is a tokamak, in which strong magnetic fields confine a torus-shaped fusion plasma. There are potential abnormal operating environments where the plasma currents inside the tokamak are disrupted and induce eddy currents in the shield modules. These currents interact with the large magnetic fields to produce forces in the modules which could potentially cause mechanical failure in the modules and vacuum vessel.

The purpose of this presentation is to describe the electromagnetic analysis that has been completed as part of the conceptual design using the OPERA-3d[1] product to characterize the forces on the shield modules allocated to the United States. This software package has a number of key features needed for the analysis of interest. It solves the vector potential formulation of Maxwell's equations suitable in the eddy current regime for transient excitation. In addition, symmetry can be used to reduce the number of unknowns and finally forces can be computed and results exported to user defined mesh files. We first describe the electromagnetic model of the system which consists of the shield modules in the presence of the vacuum vessel and the disruption currents that induce eddy currents in the modules. Once the modeling procedure has been described the simulation results will be presented. The force computation on a selected number of shield modules will also be presented and the results discussed.

II. Electromagnetic Modeling

A. Shield Model

The solid models of the shield modules used for the electromagnetic analysis are of course a simplification of the actual devices. For example a cutaway view of shield module 7 is shown in Fig. 1. In this view one can see features inherent in any module – cooling tubes, slits to reduce eddy current generation, and cut outs for mounting the shield module to the vacuum vessel.

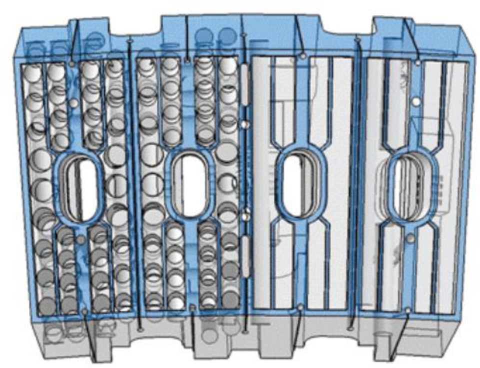

Figure 1. Shield module 7- cutaway view.

A mesh of the simplified shield module geometry used in the electromagnetic simulation is shown in Fig. 2.

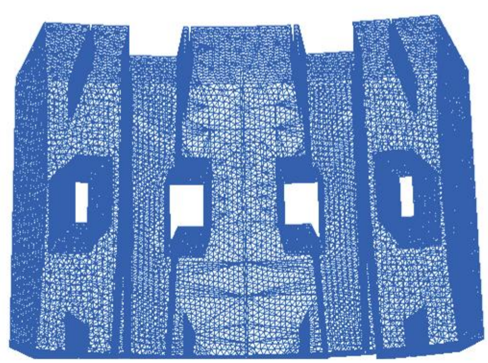

Figure 2. Simplified shield module 7 for electromagnetic calculations.

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The holes and cutouts have been preserved together with the slits in the module. The key simplification is the removal of cooling tubes. One would expect that this simplified model would predict higher forces because the block is modeled as solid.

B. Shield Modules and Vacuum Vessel

To accurately calculate the electromagnetic quantities the geometry has to be modeled appropriately. There are two models to consider – one is a ten degree sector of all the modules with the vacuum vessel while the other is a twenty degree model that includes the shield modules that the United States is responsible for. These are shown in Fig. 3 and 4.

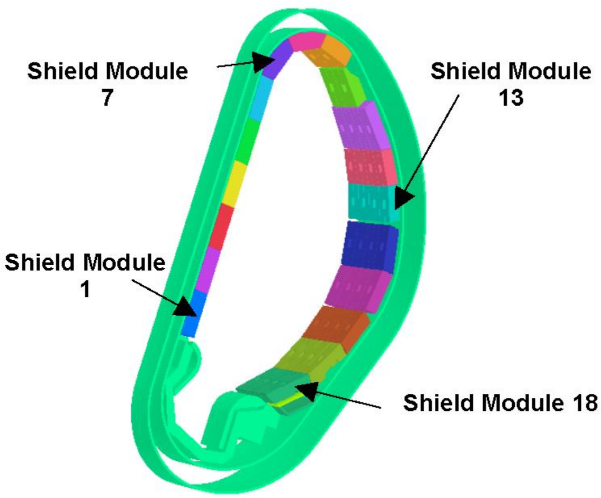

Figure 3. Ten degree sector solid model with all shield modules

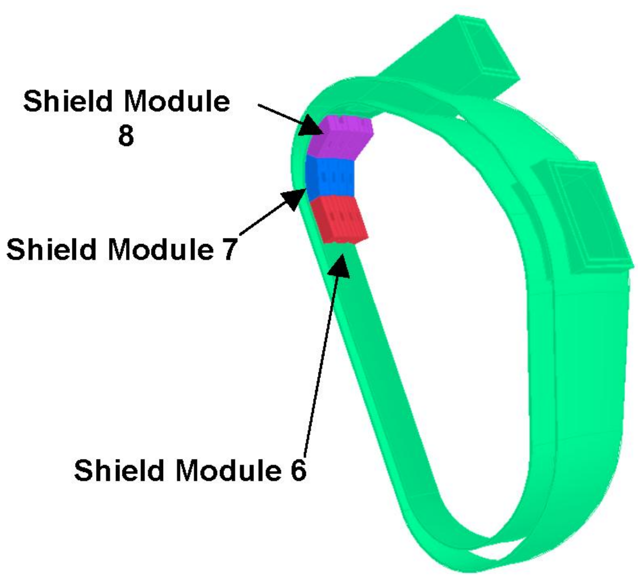

Figure 4. Twenty degree sector model with emphasis on shield module 7.

Each module in the previous figures are modeled as homogenous stainless steel and electrically isolated from the vacuum vessel.

C. Disruption Currents

There are a number of different disruption cases to consider. These have been identified by the ITER Organization using the DINA[2] code to predict plasma current behavior. The key feature of the disruption current simulation is the variation of the current both temporally and spatially within the vacuum vessel. There are two main disruption cases.

The first is termed major disruption (MD). This disruption consists of two main phases: 1) a rapid thermal quench that causes a flattening current profile that results in an increase in plasma current and 2) a current quench phase where the plasma current then drops to zero. The functional behavior of the current quench phase is not known so two different cases were prescribed. The first is termed linear where the current linearly goes to zero while the other is exponential – an exponential decay of the current. The overall plasma current for these cases is shown in Fig. 5.

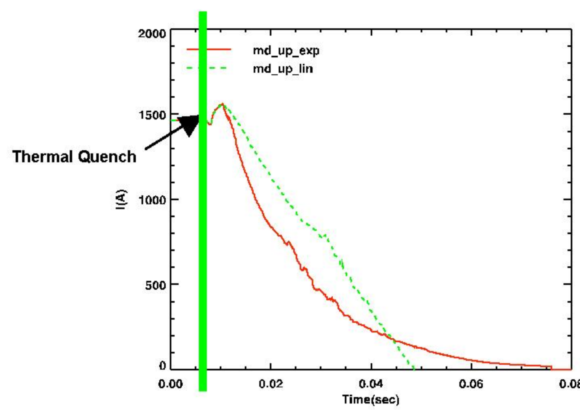

Figure 5. Major Disruption current time response for the linear and exponential cases.

The other disruption is termed Vertical Displacement Event (VDE). During this disruption the plasma starts a slow vertical drift and contacts the first wall which results in halo currents in the first wall structure. The time behavior for this case is similar to that shown in Fig. 5, except that thermal quench occurs at 630ms. For this initial analysis the halo currents are neglected.

In addition to the temporal variation there is also a spatial variation of the plasma currents. This spatial variation is modeled by using a superposition of toroidal solenoids with different weights and time variation. The sum of these currents results in the waveforms of Fig. 5 and also includes the appropriate spatial variation as identified with the DINA[2] analysis results. The DC magnetic fields have two components – toroidal and poloidal. The toroidal field is modeled by a line source while the poloidal field is modeled using a superposition of cylindrical solenoids. The placement of these different sources with respect to the modules and vacuum vessel is shown in Fig. 6.

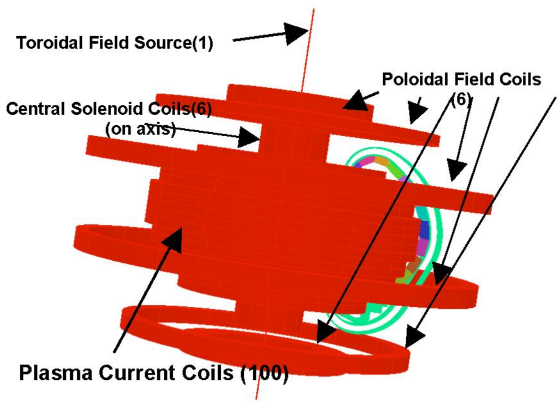

Figure 6. Current sources use to model disruption and DC magnetic fields.

D. Overall Model

Once the excitations and geometry have been identified the next step is to produce a mesh. A key feature in the OPERA-3d modeling software is the ability to use periodic symmetry for the model. This allows the use of a smaller mesh without compromising the electromagnetic simulation. The mesh size for the different simulations is collected in Table I.

Table I. Mesh size information for the different models.

Sector (Degrees)	Modules	Element Count
10	1 through 18	~3 million
20	6-7-8	~ 3.6 million
20	11-12-13-14	~4.6 million

III. Results

Some results of the different numerical simulations will now be described. We will present some eddy current plots to reveal the current flow pattern in selected shield modules. Then the forces will be calculated as a function of time and also shown and discussed.

A. 10/20 degree sector for shield module 7

Shield module 7 for the 10 degree sector is physically one half of module in the 20 degree model. The eddy current magnitude and vector representations are shown in Fig. 7.

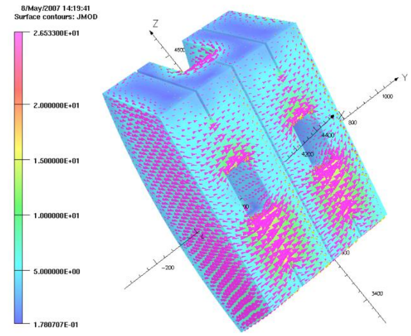

Figure 7. Eddy currents in SM 7, 10 degree sector, D1, t=.48ms.

D1 refers to the major disruption with a linear current decay, and SM refers to shield module. The qualitative behavior of the current is consistent with the direction of the disruption currents. The eddy currents flow around the openings and slits in the metal block as expected.

The forces in the modules are due to the interaction of the eddy currents induced in the modules with the magnetic fields[3].

$$\bar{F} = \iiint_{vol} \bar{J} \times \bar{B} dv \qquad (1)$$

This computation is performed by the post-processor in OPERA-3d. The eddy current as well as the magnetic flux density can be exported on a user defined grid. This will be used to look at the stress distribution and torque that the shield module will undergo as a result of the disruption currents.

The x-component of the forces computed for SM 07 for the two different models is shown in Fig. 8. The x-component of force is in the direction away from the vacuum vessel wall toward the center of the device.

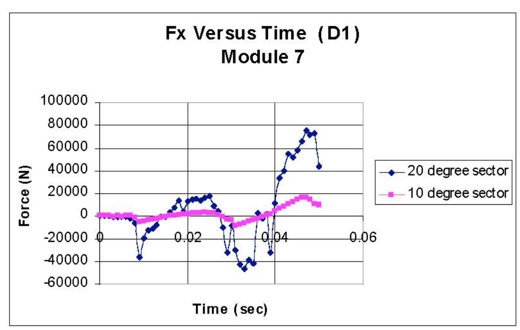

Figure 8. Force comparisons for two models – SM 07.

The two force computations clearly reveal substantially different behavior. This comparison shows that cutting the module in half perturbs the eddy current distribution in a non-intuitive manner – they are not different by a simple multiplicative factor.

B. 10/20 degree sector model for shield module 13

Shield module 13 for the 10 degree sector is the full module while 20 degree sector model consists of two of these modules placed side by side. The eddy current distribution is shown in

Fig. 9. The view for this figure is shown from the top revealing the eddy current flow around the slits in the module.

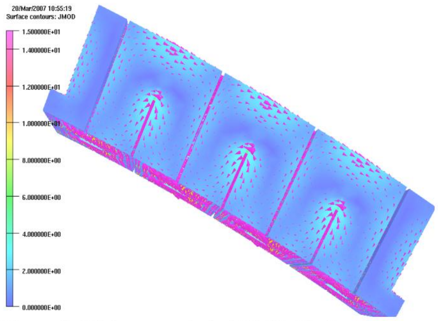

Figure 9. Eddy currents in SM 13, 10 degree sector, D1, t=.46ms

The y-component of the forces computed for SM 13 for the two different models is shown in Fig. 10. The y-component of force is in the direction along the vacuum vessel wall.

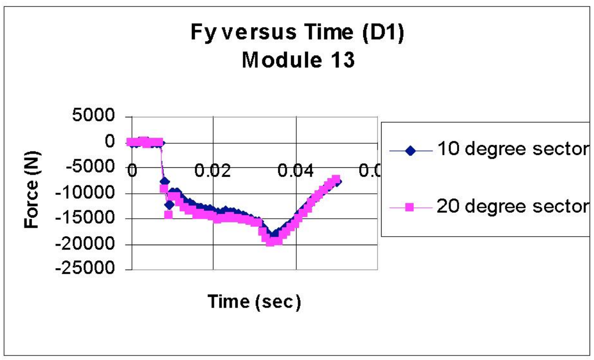

Figure 10. Force comparison for two models – SM 13.

The comparison shown in Fig. 10 reveals that the two models do capture the electromagnetic behavior and therefore the forces accurately.

IV. Conclusions

The calculation of forces due to the disruption of plasma currents on different shield modules in the ITER device has been demonstrated. The simplified models of the shield modules used for the electromagnetic analysis have also been shown together with the distributed modeling of the plasma disruption currents. The simplification of the model has shown to give good agreement as well as poor agreement when the simplifications have substantially changed the electromagnetic behavior of the shield modules in the presence of the fields and disruption current.

Future work will look to incorporate more detailed models of the shield modules that include the cooling tubes. In addition new disruption cases need to be considered as supplied by the ITER Organization[4]. Finally these forces will be incorporated with other force computations (thermal, etc.) to accurately calculate the total stress and torque on each module.

References

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